

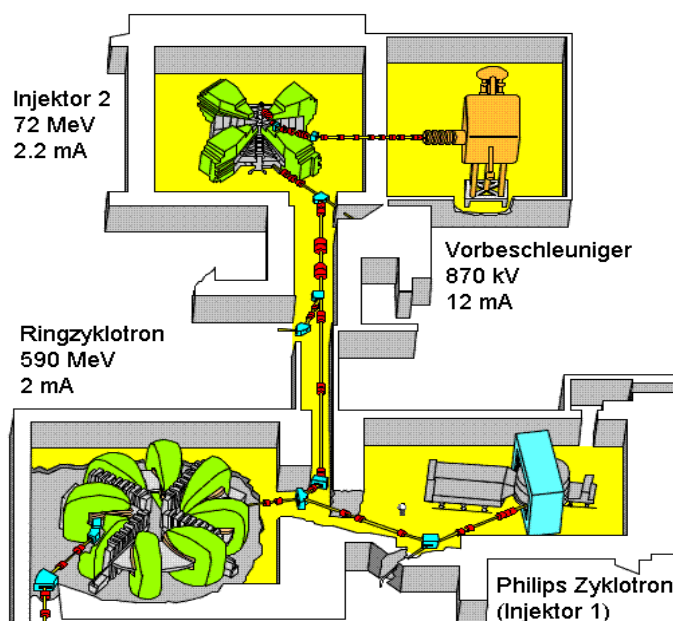
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The PSI High Intensity Cyclotron and its Extrapolation to a 10 MW Driver

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The acceleration of a 2 mA, 590 MeV proton beam has been demonstrated at the PSI High Intensity Cyclotron. The peculiarities of the machine, the operation mode for high currents, and the ongoing upgrade program are discussed. The conceptual design of a 10 MW driver based on the extrapolation of the present performances is presented.

Der PSI Hochstrombeschleuniger



- Introduction: The PSI Proton Accelerator Facility
- The injector 2: Injection/acceleration of a space charge dominated beam
- The Ring Cyclotron: rf improvement programm: past and future
- Extrapolation to a 10 MW Driver (The Dream Machine)

Accelerator Facilities

- C Cockcroft-Walton
- I2 Injector 2
- R 590 MeV Ring Cyclotron
- I1 Injector 1

Beam Transport Lines

- P Proton Channel

Neutron Spallation Source

- S Neutron Spallation Source SINO
- L Target-Storage Pit

Medicine

- 1 Isotope Production IP2
- 2 Eye Treatment OPTIS
- 3 Proton Therapy Gantry

Nuclear Physics and Radiochemistry

Particle Physics

Solid State Physics and Materials Science

NA-Hall

Experimental Hall

Neutron Guide Hall

Driftal

NCR

TOPS

TASP

NDB

PGA

SANS

FOCUS

AMOR

ATEC

GPS

LTF

PIF

PIREX

MOPE

πM3

πE5

πE3

πE1

NE1

NE-B

NE-C

Target-M

Target-E

SINQ Target Hall

FUNSPIN

NAA / PNA / GJA

TIICS

HRPT

NEUTRA

POLDI

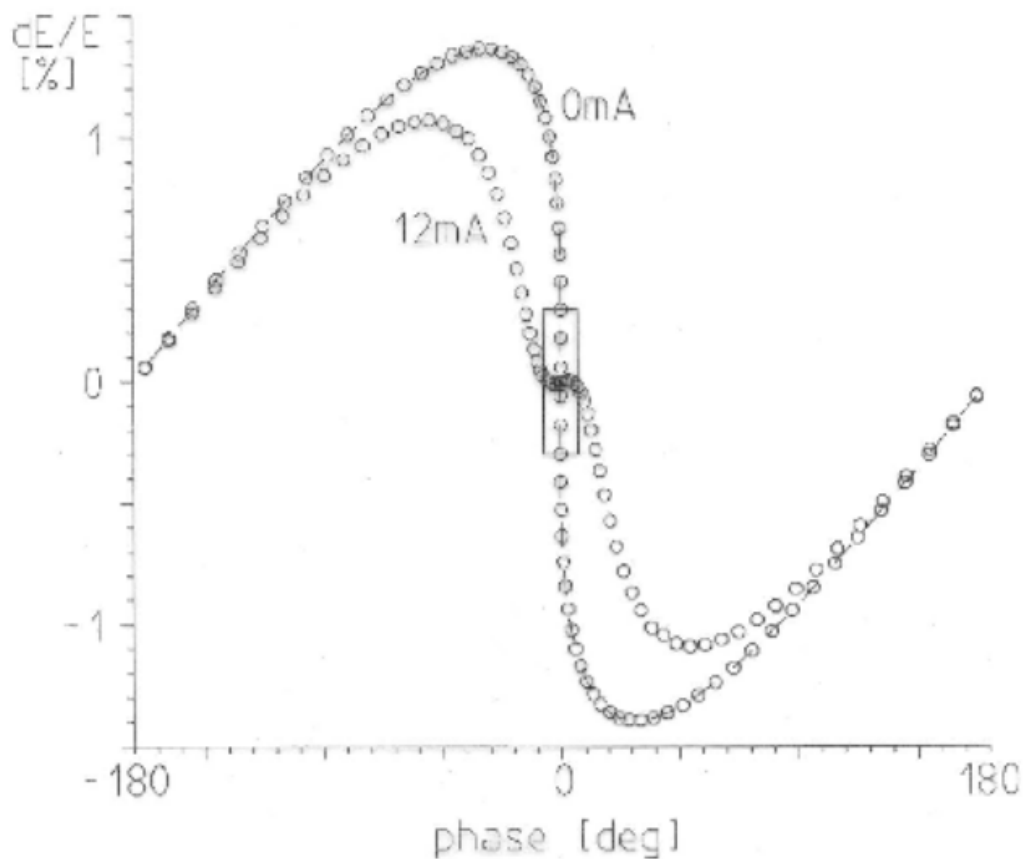
Bunching under space charge dominated conditions

(or: "Space charge compensated bunching")

- action of space charge forces in a bunched beam

calculated using SPUNCH (R.Baartman, Tokyo 1986)

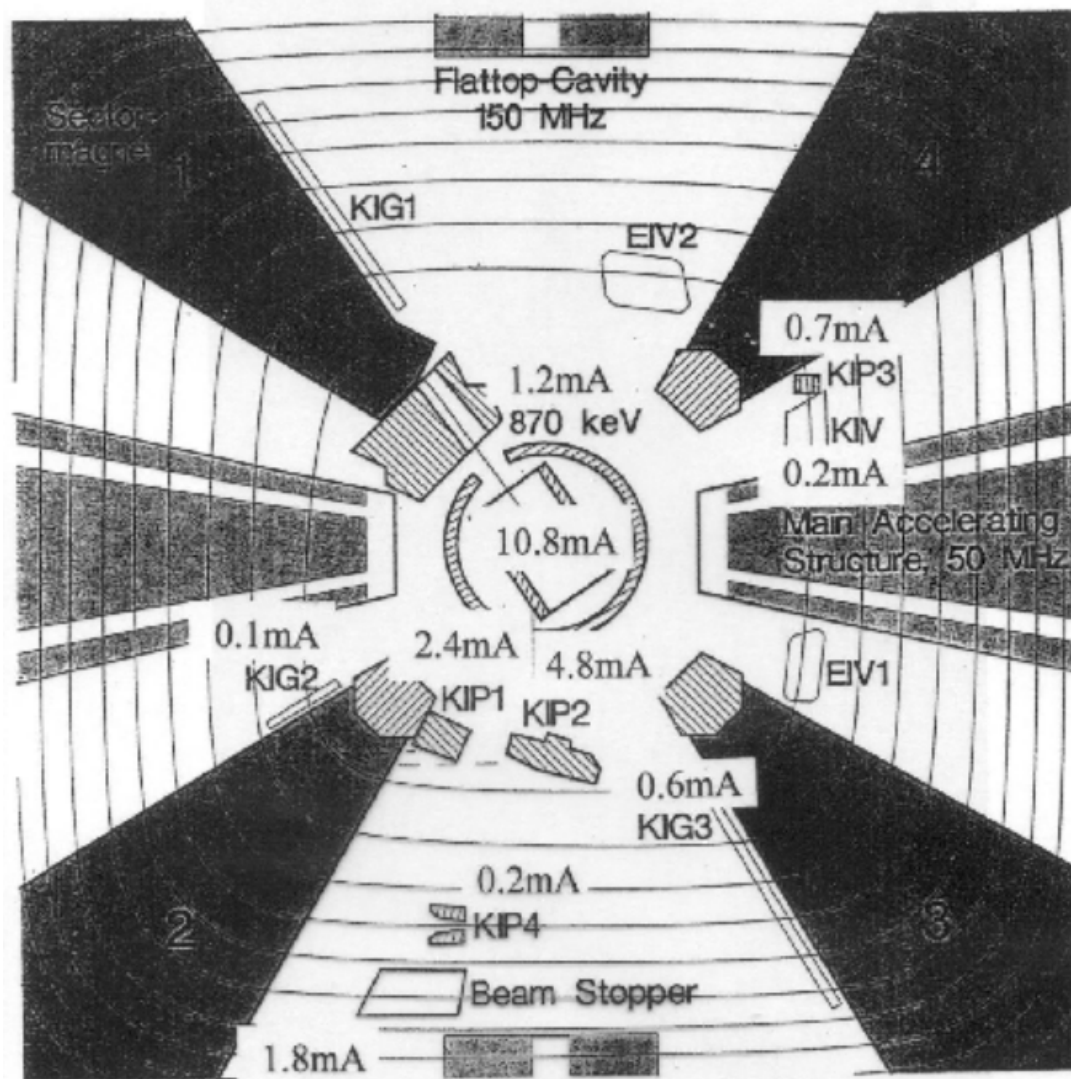
5deg initial phase / dot



- ==> energy spread is reduced, if DC beam current, buncher voltage and buncher distance are selected corresponding to each other
- ==> bunching factor ~ 3 for lowest energy spread

Beam collimation in the centre region Inj.2

- ion source DC beam current	12.0mA
collimators in the 870keV beam transport line	1.2mA
- injected beam current	10.8mA
phase defining collimator (KIP1 & KIP2)	7.2mA
- beam current accepted on the 1 st turn	3.6mA
collimation of phase tails on the 1 st turn (KIP3)	0.7mA
vertical collimation (KIG1,KIG2,KIG3,KIV)	0.9mA
radial collimation on the 4 th turn (KIP4)	0.2mA
- accelerated beam current	1.8mA



Beam matching at high beam intensities PSI Inj.2

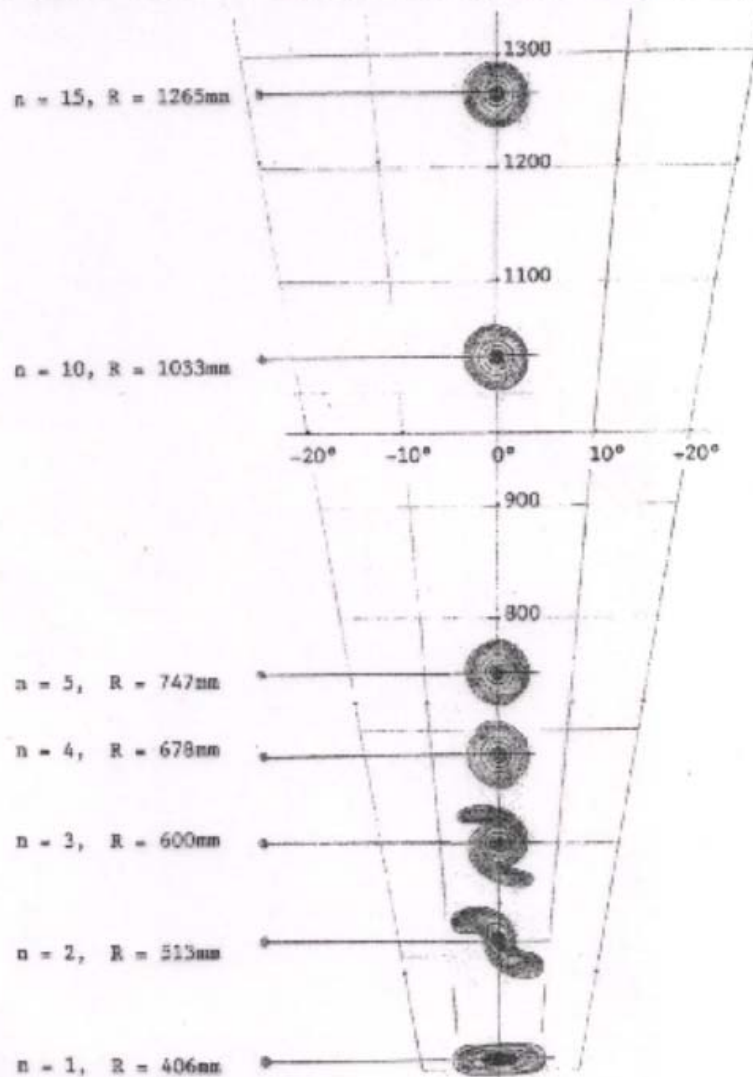
- longitudinal space charge effects are strong in cyclotrons, and radial and longitudinal motion are strongly coupled

⇒ at high currents the beam has to be matched in 6 dimensions

⇒ circular bunch is a stable configuration under space charge

- simulation
PSI Inj.2,
1.5mA
contours lines
10,20,50,80%
(Adam 1985)

$R \uparrow$
 $\rightarrow \varphi$

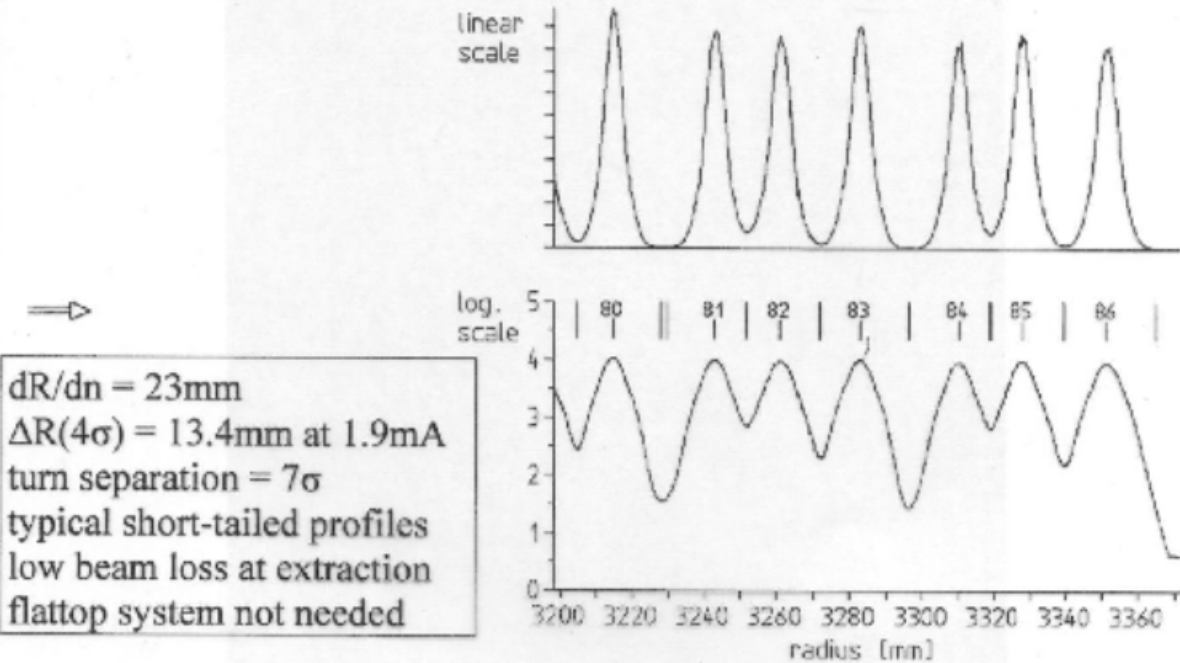


- note:

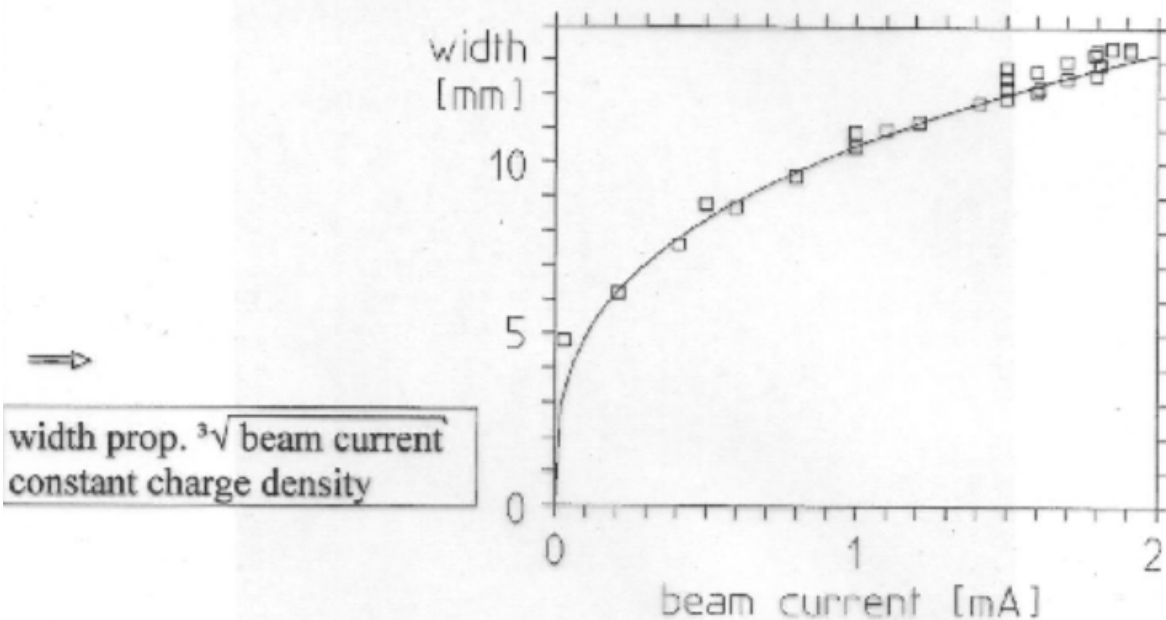
- a circular bunch in radius and phase is stable under acceleration,
- $dl = dR = \pm 6\text{mm}$ corresponds to 17deg fw at injection,
- phase width becomes extremely narrow at extraction, $\sim 2\text{deg}$
- a slightly mismatched bunch is captured into the matched phase space (Adam, Koscelniak, PAC 1993)

Inj.2: turn profiles & extraction

- beam profile of the last 7 turns, 72MeV



- width in function of the extracted beam current



- injector for a 10MW beam facility, 1GeV/10mA

tentative layout:

4 sectors, $E = 120\text{MeV}$

4 resonators, $E_{\text{gain}} = 2. - 2.5\text{MeV/turn}$

$dR/dn = 27.6 - 34.5\text{mm}$

$\Delta R(4\sigma) = 23.3\text{mm}$ at 10mA

⇒ turn separation = $4.7\sigma - 5.9\sigma$

⇒ use off-centre injection in order to increase turn separation

open questions:

can an RFQ be used as preinjector

what beam quality can be expected with 10mA

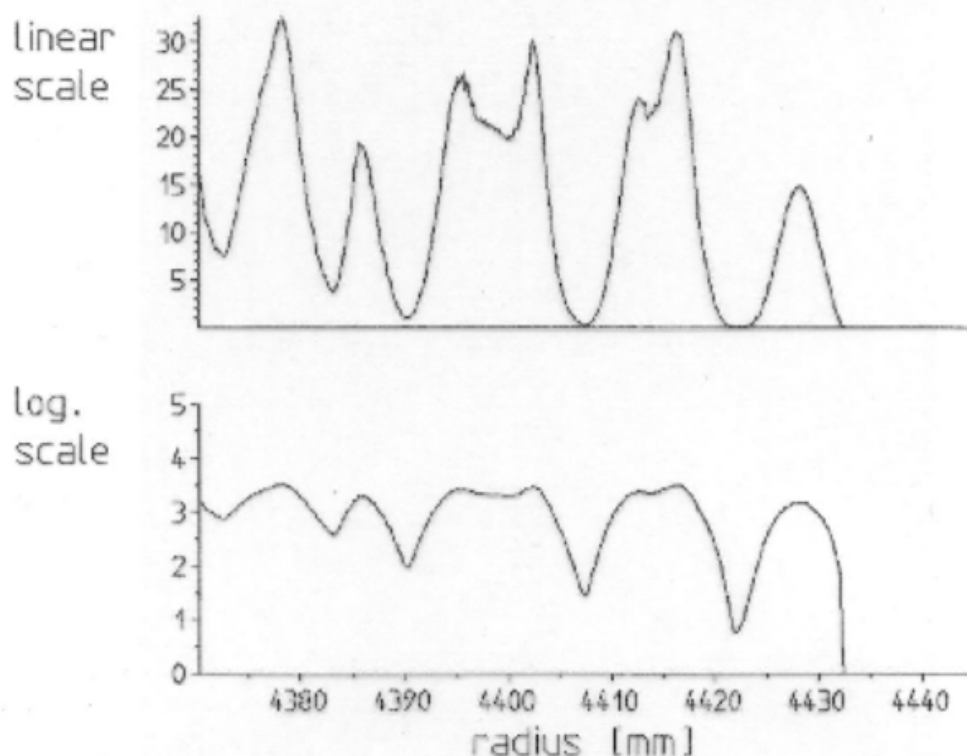
does better longitudinal matching reduce ΔR

⇒ full 6 dimensional space charge simulation needed

⇒ 6 dimensional tracking code is being developed

PSI 590MeV Ringcyclotron: extraction of the beam

- beam profiles of the last 12 turns in the Ringcyclotron, 1.8mA



⇒ $dR/dn = 12\text{mm}$
 $\Delta R(4\sigma) = 6.8\text{mm}$ at 1.8mA
 turn separation = 7σ
 low beam loss at extraction,
 annually averaged extraction rate 99.98% at 1.5 - 1.8mA

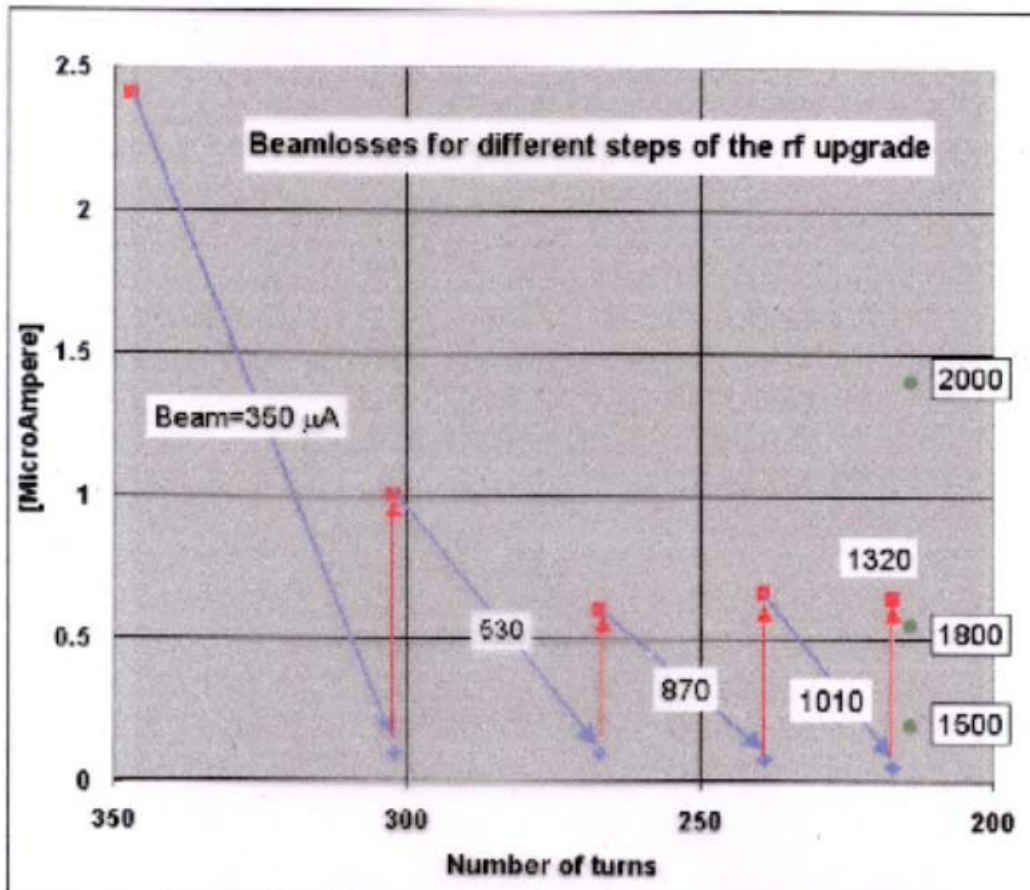
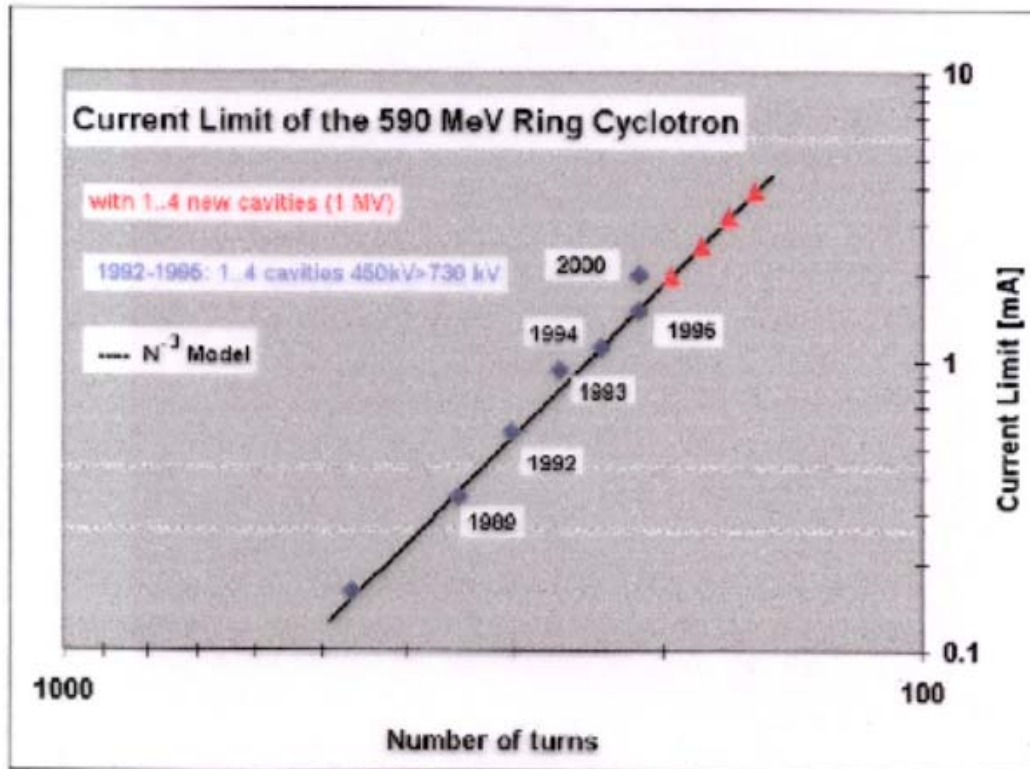
⇒ turn separation doubled with a large betatron oscillation
 introduced by off-centre injection
 turn separation optimised by a moderate mismatch of the
 radial phase space & the dispersion trajectory

- longitudinal space charge effects

⇒ phase of the flattop system is an important parameter to
 optimise the turn profiles at extraction

Joho's rule on turn separation is confirmed experimentally:

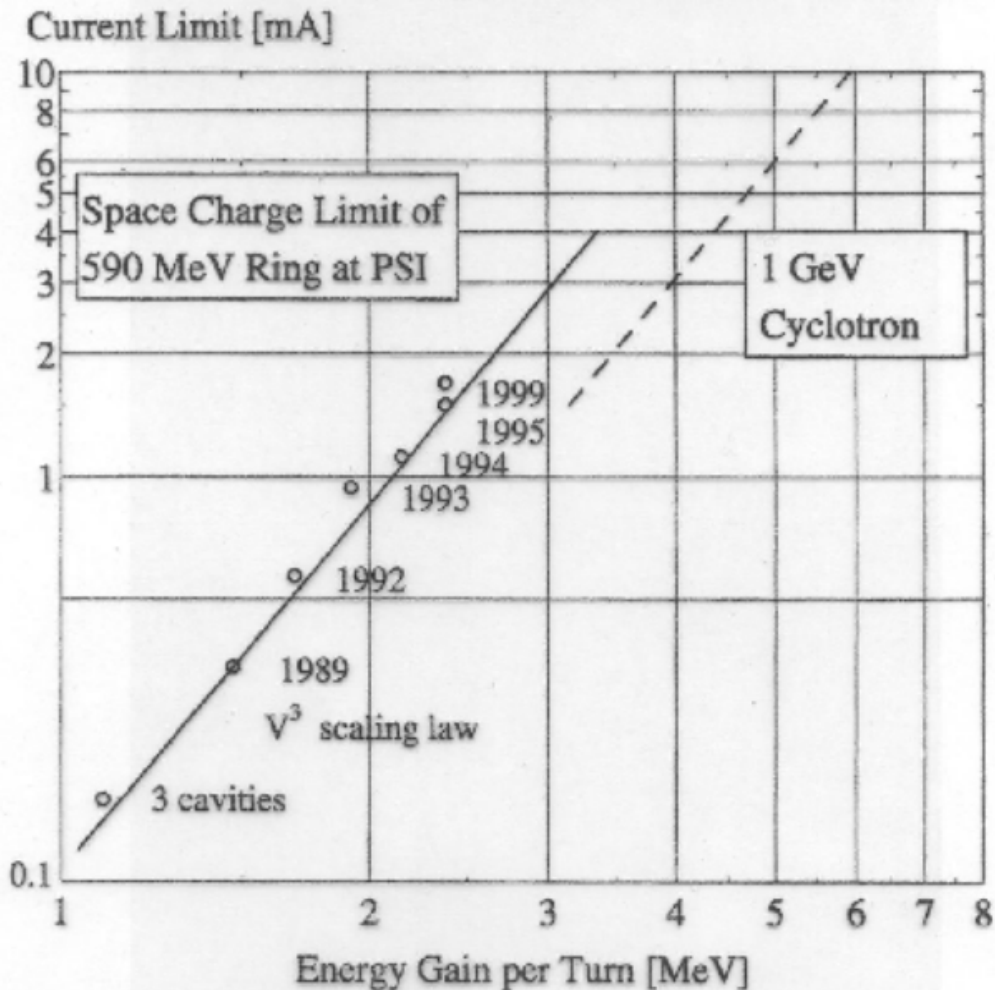
$$E_{\text{gain}}/\Delta E_{\text{sc}} \text{ is prop. to } N^3$$



Space charge effects & extrapolation to a 10MW facility

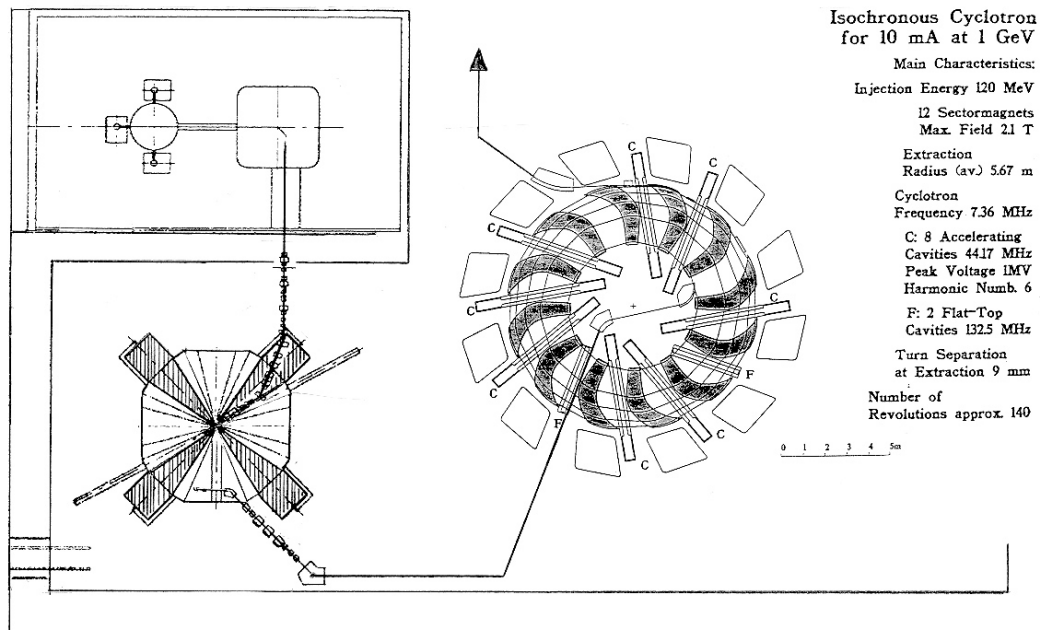
- note: longitudinal effects add up over all revolutions N
 ΔE_{sc} prop. to N for separated turns
to N^2 for overlapping turns (Joho 1981)

\Rightarrow turn separation ($E_{gain}/\Delta E_{sc}$) is prop. to $(1/N^3) \approx (E_{gain})^3$



\Rightarrow **PSI Ring:** $I_{max} = 4mA$ with 1MV cavities ($E_{gain}=3.3MeV$)
1GeV cycl: $I_{max} = 10mA$ with 8 cavities ($E_{gain}=6.3MeV$)

Conceptual layout of a 10 MW Driver:



Comparison PSI Cyclotrons vs 10 MW driver:

	PSI Injector 2	120 MeV
Energy	72 MeV	120 MeV
Beam Intensity	2.2 mA	10 mA
Cavities	2 + 2 Flattop (now used for acceleration)	4 Egain: 2-2.5 MeV/turn
dR/dn	23 mm	28-35 mm
$\Delta R(\sigma)$	13.4 mm at 1.9 mA	23 mm
	PSI Ring	1 GeV
Magnete	8	12
Cavities	4 (730 kV)	8 (1000 kV)
Flat top	1 (460 kV)	2 (650 kV)
Rav	4462 mm	5677 mm
Number of turns	215	140
Egain at extraction	2.44 MeV	6.3 MeV
Number of turns	215	140
$dR/dn = (R_{av} \gamma / (\gamma + 1) v_r^2) (E_{gain} / E)$	5.7 mm	10.7 mm
x 2 with betatron oscillation	12 mm	
$\Delta R(\sigma)$	6.8 mm at 1.8 mA	
Turn separation	7 σ	7 σ
Space charge limit	2 mA (4 mA expected with 1000 kV cavities)	10 mA
Beam power	1.18 MW (2.36 MW)	10 MW